

Stratospheric aerosol and gas experiments I and II comparisons with ozonesondes

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Abstract. Ozone profiles measured by the Stratospheric Aerosol and Gas Experiments (SAGE) I and II are compared with ozonesonde profiles at 24 stations over the period extending from 1979 through 1991. Ozonesonde/satellite differences at 21 stations with SAGE II overpasses were computed down to 11.5 km in the midlatitudes, to 15.5 km in the lower latitudes, and for nine stations with SAGE I overpasses down to 15.5 km. The set of individual satellite and ozonesonde profile comparisons most closely colocated in time and space shows mean absolute differences relative to the satellite measurement of $6 \pm 2\%$ for SAGE II and $8 \pm 3\%$ for SAGE I. The ensemble of ozonesonde/satellite differences, when averaged over all altitudes, shows that for SAGE II, 70% were less than 5%, whereas for SAGE I, 50% were less than 5%. The best agreement occurred in the altitude region near the ozone density maximum where almost all the relative differences were less than 5%. Most of the statistically significant differences occurred below the ozone maximum down to the tropopause in the region of steepest ozone gradients and typically ranged between 0 and -20% . Correlations between ozone and aerosol extinction in the northern midlatitudes indicate that aerosols had no discernible impact on the ozonesonde/satellite differences and on the SAGE II ozone retrieval for the levels of extinction encountered in the lower stratosphere during 1984 to mid-1991.

Introduction

Over the last 3 decades, vertical profiles of ozone extending from the ground into the lower stratosphere have been routinely measured by balloon-borne instruments (ozonesondes) at a number of stations located predominantly in the northern hemisphere. With the advent of space-based platforms it became possible to measure ozone profiles with expanded coverage over the Earth. The longest record of satellite-based high vertical resolution ozone profiles has been generated by the Stratospheric Aerosol and Gas Experiments (SAGE) I and II, both developed at NASA Langley Research Center [McCormick *et al.*, 1979; Mauldin *et al.*, 1985]. Both the ozonesonde and the satellite data have been extensively used to quantify the processes governing atmospheric ozone variation. This paper presents the results of a statistical comparison designed to estimate any altitude dependent relative bias between the ozonesonde and the satellite measurements.

SAGE I and SAGE II are conceptually identical multi-channel spectrophotometers which sense solar intensity through a slant path in the atmosphere as the instrument orbits into (sunset) or out of (sunrise) the Earth's shadow. Ozone measurements are made in the Chappuis region of the

spectrum at 600 nm with a vertical resolution of 1 km through a slant path in the atmosphere approximately 220 km in length at any given altitude. The quality of the measurement in the lower stratosphere depends primarily on the extent to which interfering species such as aerosols or other absorbers can be accurately removed in the ozone retrieval [Chu and McCormick, 1979; Chu *et al.*, 1989]. In addition to the 600 nm channel, SAGE I utilized transmission measurements at 1000, 450, and 385 nm while SAGE II utilizes channels at 1000, 940, 525, 453, 448, and 385 nm to characterize other species. The ozone measurement's quality in the troposphere is impacted by the presence of clouds and aerosols in the instrument field of view. A unique aspect of the solar occultation measurement is that long-term sensor drift is effectively removed via an exoatmospheric calibration made during every profile measurement [Watson *et al.*, 1988]. Cunnold *et al.* [1989] provided the following error estimates for SAGE I and SAGE II in the altitude region of 24–36 km: 7% systematic bias, 5% random error, and reference altitude uncertainties of 0.25 km (SAGE I) and 0.2 km (SAGE II). An analysis of the error budget of the difference between SAGE I and SAGE II ozone retrievals over these altitudes yields an expected systematic error of 6% at 20 km and 2% between 25 and 30 km [Watson *et al.*, 1988].

One characteristic of the occultation measurements is that the instrument makes at most one sunrise and one sunset profile per orbit. The orbital inclinations of SAGE I and II

yield patterns of observations whose latitudes vary slowly with time. The latitudes ranging from 80°S to 80°N are sampled in a period of about 1.5 months; however, only the range from 50°S to 50°N are sampled every season of the year. SAGE I was launched in February 1979 and operated until November 1981. SAGE II was launched in October 1984 and continues to provide measurements. Studies using the SAGE II ozone data set have included analyses of the ozone quasi-biennial and semiannual oscillations (QBO and SAO), Antarctic and Arctic springtime ozone variabilities, and global ozone trends [McCormick and Larsen, 1988; McCormick et al., 1989a,b; Zawodny and McCormick, 1991].

Ozonesondes are launched on balloons at various stations throughout the world at regular intervals. The types of sondes in most common use are the electrochemical concentration cell (ECC) [Komhyr, 1969; Komhyr and Harris, 1971], the Brewer-Mast (BM) bubbler [Brewer and Milford, 1960], and the carbon-iodine (CI) sonde [Komhyr, 1965]. Each of these sondes employs the same method whereby ozone is measured by pumping ambient air through an electrolytic cell containing a buffered potassium iodide solution where ozone oxidizes the iodide into iodine. The resultant cell reaction current is directly proportional to the ozone concentration in the cell. The major differences between sonde types lie in the design of the cell and the electrolyte concentrations. All ozonesondes are flown on a balloon with a radiosonde for pressure and temperature data. After data reduction the ozone is converted into units of partial pressure.

Above the burst altitude of the balloon the upper level ozone amount must be taken into account if the integral of the ozonesonde profile is to be used to estimate total ozone above the station. During data reduction, the residual ozone above the burst altitude is estimated by extrapolation of the measured profile along contours of constant mixing ratio. Furthermore, the ozonesonde output is not an absolute measurement of the ozone profile, since ozone losses occur within the instrument, and the instrument has a finite response time [De Muer and Malcorps, 1984]. In order to compensate for these deficiencies it has been general practice to multiply the measured ozone profile by the ratio of the total ozone amount measured at the site by a Dobson spectrophotometer to the total ozone amount derived from integration of the ozonesonde profile. This ratio, called the correction factor, is used by almost all stations as an altitude independent scaling factor which makes the measured ozonesonde profile consistent with the Dobson measurement. However, in some cases the correction factor is not available in the ozonesonde data set. A large deviation of the correction factor from unity is usually indicative of measurement errors in the ozonesonde profile. Tabulated mean correction factors indicate that correction factor deviations are, on average, less than 20% and depend on the station [Logan, 1985]. Some stations exhibit temporal trends in the correction factors indicating long-term changes in sonde flight calibration [Tiao et al., 1986].

Systematic errors in the ozonesonde measurement can arise from altitude-dependent pump efficiency [Komhyr and Harris, 1965; Torres, 1981; Harder, 1987], background current correction [Komhyr and Harris, 1971; Thornton and Niazy, 1982, 1983], frequency response of the sensor and air-sampling system [De Muer and Malcorps, 1984], electro-

lyte concentration, extrapolated upper level column amount, and altitude determination [Schmidlin, 1988]. Tests conducted on ECCs in a controlled laboratory environment indicate an accuracy of 3–5% positive error from 300 to 50 hPa and 10% from 50 to 15 hPa with precision estimates of 5–6% from 200 to 10 hPa [Barnes et al., 1985]. These results are in overall agreement with the Balloon Ozone Intercomparison Campaign (BOIC) which was designed to assess the accuracy and precision of atmospheric ozone measuring instruments [Hilsenrath et al., 1986]. ECC ozonesonde error assessments performed by Komhyr et al. [1994] indicate 6% accuracy and 3% precision from 100 to 10 hPa.

Other SAGE I/II Comparisons with Ozonesondes

Several comparisons between SAGE I/SAGE II and ozonesondes have been performed largely as satellite instrument validation studies not specifically addressing the possibility of altitude dependent systematic relative biases between the two ozone measuring methods [McCormick and Reiter, 1982; McCormick et al., 1984; Attmannspacher et al., 1989; Cunnold et al., 1989; Margitan et al., 1989; WMO, 1990; Barnes et al., 1991; De Muer et al., 1990; McDermid et al., 1990]. De Muer et al. [1990], for example, analyzed a sample of 24 colocated profile pairs (0.3 day and 600 km) at Uccle. The SAGE II/Brewer–Mast differences over the altitude range from 10–26 km indicated SAGE II was lower in column amount by 4% than the sondes. On the other hand, SAGE II was higher than the sondes by 3.3% between 26 and 31 km. In Barnes et al. [1991], samples of 14 SAGE II profiles were compared with seven ECC profiles during a correlative mission at Natal, Brazil, in March and April 1985, and a difference profile was estimated over the altitude range from 17.5 to 24.5 km. From 20.5 to 24.5 km, SAGE II was within 0.5% of the ECC measurements. Below 20.5 km the 95% confidence intervals were large due to atmospheric variability and included 0%. Cunnold et al. [1989] computed the relative difference between a sample of five colocated measurements between SAGE II and ECCs over the altitude range from 15.5 to 25.5 km, and their results were consistent with those presented herein. Cunnold and Veiga [1991] presented a comparison between SAGE I/II and ozonesondes which showed larger ozonesonde/SAGE I differences than ozonesonde/SAGE II differences and general altitude dependent differences maximizing between 16 and 18 km. The work presented herein is an extension of their method which utilizes an expanded set of ozonesonde and SAGE I/II data.

All of the previous published comparisons described above were performed using a version of the SAGE II data set earlier than that used here. The version used here (version 5.9) has improvements in the aerosol correction to the ozone below 15 km, and a long-term time-varying mirror reflectivity correction which affects ozone concentration above 50 km.

Data Description

The fundamental SAGE I/II measurement of ozone is number density as a function of geometric altitude at 1 km increments. Transformation to a pressure altitude coordinate involves using National Meteorological Center (NMC) data

interpolated to the SAGE I/II location, a procedure which adds an unnecessary level of uncertainty. Thus the comparisons were performed on a geometric altitude scale by transforming the ozonesonde data from pressure altitude to geometric altitude. The rationale for using this altitude coordinate is that the ozonesonde pressure and temperature measurements represent a more accurate representation of local conditions than do the pressure and temperature data interpolated from the NMC-gridded analysis. The ozonesonde profiles were mapped to a geometric altitude scale using the hypsometric equation with gravitational acceleration variable with latitude and altitude [List, 1951]. No humidity data were available for the ozonesonde profiles, and thus the mean molecular weight was assumed constant. Ozonesonde measurements were converted from partial pressure to number density. There are errors inherent in using the hypsometric equation to obtain geometric altitude and in converting partial pressure to number density from radiosonde pressure and temperature measurements. *Parsons et al.* [1984] compared highly accurate radar altitudes with altitudes constructed through the hypsometric equation using U.S. radiosonde measurements, and they derived altitude errors (rms) of up to 600 m at 30 km and 250 m at 25 km. *Schmidlin* [1988] intercompared radar altitudes with hypsometric altitudes derived from closely matched multiple soundings of several well-calibrated radiosonde types in worldwide use. Their results were inconclusive regarding the sign of any potential altitude difference. Near 18 km the radiosonde/radar altitude difference and standard deviation were both less than approximately 100 m, indicating relatively good agreement among the various sonde types. However, near 24 km both the altitude difference and standard deviation ranged from 100 to 500 m among the sonde types.

Most of the profiles in the ozonesonde database are corrected for the total ozone amount as part of the standard data reduction process at the ozonesonde station. Profiles from stations for which the Dobson correction is not applied as part of the standard data processing were corrected for this study. Furthermore, each ozonesonde profile was multiplied by 0.9743 to account for the currently accepted ozone cross sections used in the Dobson measurement [Bass and Paur, 1985; Komhyr, 1980]. Profiles were rejected from the comparison whenever the correction factors were not in the range 0.80–1.2. Profiles which had no corresponding Dobson measurement available were used with no total ozone corrections applied; however, the number of such profiles was less than 6% of the total sample size of the ozonesonde data set.

The ozonesonde/satellite sampling was set so that the satellite-altitude coordinate ranged from cloud top to approximately 32 km, and the spatial location of the profiles was taken at the latitude and longitude of the SAGE I/II 20 km tangent point. SAGE I/II profiles were not compared with ozonesondes if local meteorological data was unavailable below 25 km (used for the Rayleigh extinction correction to the satellite ozone profile). The number of ozonesonde/satellite profile pairs (a pair is defined below) used in computing a difference profile was based on a spatial-temporal window (STW) which was large enough to make the length of the 95% confidence interval on the difference smaller than 20% at some point in the altitude region near the peak of the ozone number density (21–26 km). Using this

criterion, the STWs for each station ranged from a maximum of 2 days and 1000 km to 18 hours and 600 km. If more than one SAGE I/II profile was within the STW, then all the satellite profiles in the window were compared with the single colocated sonde profile. Henceforth we shall refer to the set of ozonesonde/SAGE colocated profiles as the “paired data.”

Table 1 lists the 24 ozonesonde stations for which sufficiently large sample sizes of ozonesonde/SAGE collocations occurred during the period of 1979–1991. Most stations used the ECC. The Canadian stations (station numbers 21, 24, 76, and 77) changed from using BM sondes to ECC sondes in 1979–1980, whereas the Japanese stations (7, 12, 14, 101, and 190) used the CI sonde. Figure 1 shows the distribution of the ozonesonde station locations (triangles) superposed with the sampling locations (squares) for the sunset meridional sweep of SAGE II during March (SAGE I sampling is similar).

The SAGE I and SAGE II data set were provided by the NASA Langley Research Center, Hampton, Virginia, and were also available through the National Space Science Data Center, Greenbelt, Maryland. The ozonesonde data sets were provided by the World Ozone Data Center (WODC), Downsview, Ontario; the National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado; and the National Institute of Water and Atmospheric Research, Central Otago, New Zealand.

Difference Profiles

By utilizing the relatively large number of sampling opportunities available in the paired data, it was possible to estimate the relative systematic difference between the in situ electrochemical method and the satellite occultation method. The underlying assumption was that the effect of random variation would cancel, as the sample became large. However, the spatial and temporal separation constraints tend to keep the sample sizes from growing unlimitedly since increasing each pair's spatial separation also increases the probability of geophysically induced differences.

Vertical profiles of the percentage difference between the ozonesonde measurement and the satellite measurement referenced to the satellite measurement over the altitude range of 15.5–32.5 km (SAGE I) and 10.5–32.5 km (SAGE II) in 1 km increments were computed. The SAGE measurement was chosen as the reference since it represents the output of a unique self-calibrating instrument with constant characteristics through time, whereas the ozonesonde profiles come from a variety of stations with interunit differences.

The measure of difference chosen to estimate the ozonesonde/SAGE difference was the median percentage difference defined as

$$\Delta = 100 \cdot \text{median} \left(\frac{Y - X}{X} \right),$$

where Y represents the vector of ozonesonde measurements and X the corresponding vector of SAGE I/II measurements in the colocated sample. Ninety-five percent confidence intervals on Δ were computed using the bootstrap technique [Efron, 1982]. As a consistency check, the collection of sample fractions, $(Y - X)/X$, were also modeled with

Table 1. World Ozone Data Center Ozone-sonde Stations

Station	Latitude, deg	Longitude, deg	Elevation, m	SAGE I Period	SAGE II Period	Sonde
12, Sapporo	43N	141E	19		Oct. 1986 to June 1991	CI
14, Tateno	36N	140E	31		Nov. 1984 to April 1991	CI
21, Edmonton	54N	114W	766	Feb. 1979 to Nov. 1981	Aug. 1985 to June 1991	ECC
24, Resolute	75N	95W	64	May 1979 to Sept. 1981	Aug. 1985 to April 1991	ECC
67, Boulder	40N	105W	1743		Jan. 1985 to Feb. 1990	ECC
76, Goose Bay	53N	60W	44	March 1979 to Sept. 1981	Nov. 1984 to June 1991	ECC
77, Churchill	59N	94W	35	March 1979 to Sept. 1981	Oct. 1984 to June 1981	ECC
99, Hohenpeissenberg	48N	11E	975	Feb. 1979 to Nov. 1981	Oct. 1984 to June 1991	BM
101, Syowa	69S	40E	21		Dec. 1984 to Oct. 1990	CI
107, Wallops Island	38N	76W	13	March 1979 to Nov. 1981	Nov. 1984 to May 1991	ECC
109, Hilo	20N	155W	11		Dec. 1984 to Nov. 1990	ECC
132, Sophia	43N	23E	58		Nov. 1984 to April 1991	Unknown
156, Payerne	47N	7E	491	Feb. 1979 to Sept. 1981		Unknown
174, Lindenberg	52N	14E	98	May 1979 to Nov. 1981	Oct. 1984 to April 1991	ECC
190, Naha	26N	128E	27		Sept. 1989 to July 1991	CI
191, Samoa	14S	170W	82		July 1986 to March 1988	ECC
197, Biscarosse	44N	1W	18	May 1979 to Nov. 1981		BM
210, Palestine	32N	96W	210		May 1985 to May 1985	ECC
215, Garmisch	48N	11E	740	Feb. 1979 to Nov. 1981		BM
233, Marambio	64S	57W	198		Nov. 1988 to April 1991	ECC
254, Laverton	38S	144E	21		July 1986 to Oct. 1990	BM
256, Lauder	45S	170E	370		Sept. 1986 to Dec. 1990	ECC
262, Sodankyla	68N	27E	179		March 1989 to April 1991	ECC
265, Irene	25S	28E	1524		July 1990 to May 1991	ECC

Ozone-sonde stations for which SAGE I/II overpassed within a window of 24 hours and 1000 km. CI is Carbon-Iodine; ECC is electrochemical concentration cell; BM is Brewer-Mast.

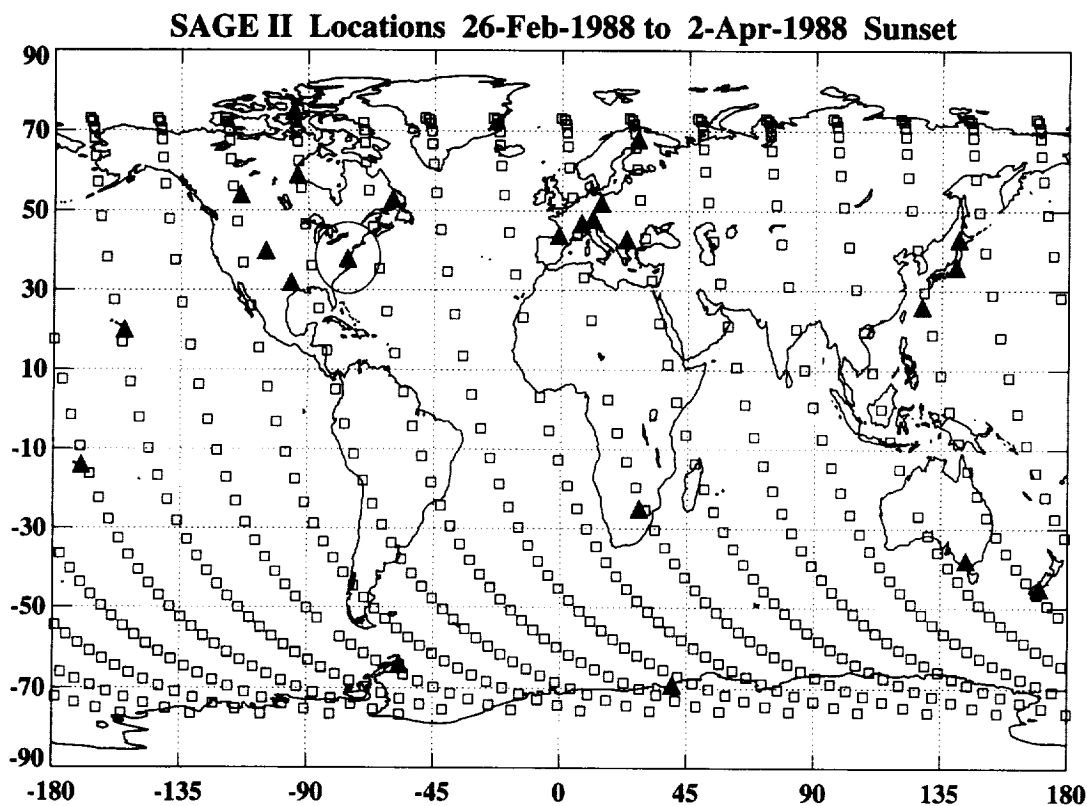


Figure 1. Ozone-sonde locations (triangles) and SAGE II sampling locations for February–April 1988 (squares). The circle around the Wallops Island station is 1000 km in radius.

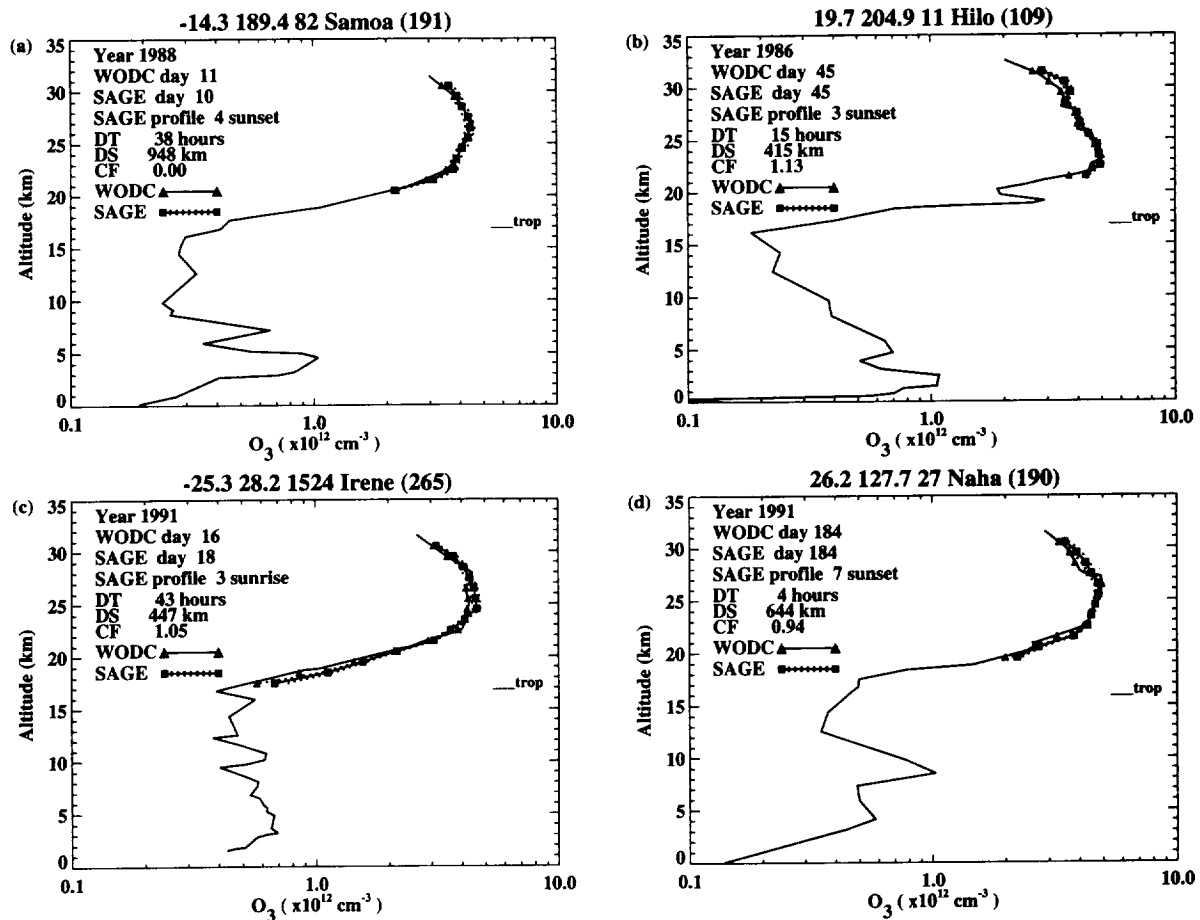


Figure 2. The closest colocated SAGE II and ozonesonde profiles from the ensemble used in calculating median difference profiles. In the legend at the upper left, DT is the time separation rounded to the nearest hour, DS is the spatial separation, and CF is the correction factor. If CF is 0.0, then no correction factor was available for the WODC profile. The approximate height of the tropopause is marked along the right axis. SAGE II data are shown down to the highest detectable cloud. The ozonesonde station's latitude, longitude, altitude (m), name, and number are written along the top of each plot.

a lognormal distribution. The mean of the lognormal served as the difference estimator, and standard confidence intervals were computed. The results from using either Δ or the lognormal approach were in good agreement except in cases where large differences caused the lognormal mean to be biased. Δ was chosen as the difference estimator instead of the lognormal mean because it is a more robust measure of central tendency whenever large deviations occur in the sample.

Results

Searching the ozonesonde and satellite databases for colocated profiles meeting the criteria described above produced a set of individual profile pairs at each station with closest agreement. These closest profile pairs are shown for each station in Figures 2 and 3 for SAGE II and SAGE I, respectively. Profile pair information appears on the upper left of each panel, with the NMC-derived height of the tropopause marked near the right axis. Ozonesonde profiles (solid line) are displayed at all available altitudes and have also been integrated in the 1 km vertical altitudes corresponding to the SAGE I/II altitudes (triangles). The SAGE I/II profiles (squares) are plotted from cloud top up along

with the 1σ uncertainty (dots). It is clear and very impressive that when the ozonesonde and SAGE I/II sampled similar synoptic conditions (Figures 2h, 2l, 2p, 2u, and 3f) that both systems agree remarkably well with respect to the large-scale features of the profile. It is obvious that features with 3–5 km vertical extent are detected by the satellite instrument as seen in Figure 2n at 14 km; 2p at 18 km; 2q at 23 km; 2s at 25 km; 2t at 18 km; 2u at 25 km; and 3i at 15 km. The two profiles at Sodankyla in 1990 (Figure 2s) show that vertically narrow laminar structures, when integrated over 1 km in the ozonesonde profile, also agree very well with the SAGE II measurements. For each of the profile pairs in Figures 2 and 3, the mean absolute difference relative to the satellite measurement was computed at each altitude. The average of these differences for the 21 ozonesonde/SAGE II pairs in Figure 2 was $6 \pm 2\%$ (1σ). For the nine ozonesonde/SAGE I pairs in Figure 3 the difference was $8 \pm 3\%$ and is in good agreement with the results of a previous SAGE I/ECC correlative measurement program [McCormick et al., 1984].

The ozonesonde/satellite median difference profiles, arranged in increasing distance from the equator, are shown in Figure 4 for the 21 stations with SAGE II overpasses and in Figure 5 for the nine stations with SAGE I overpasses.

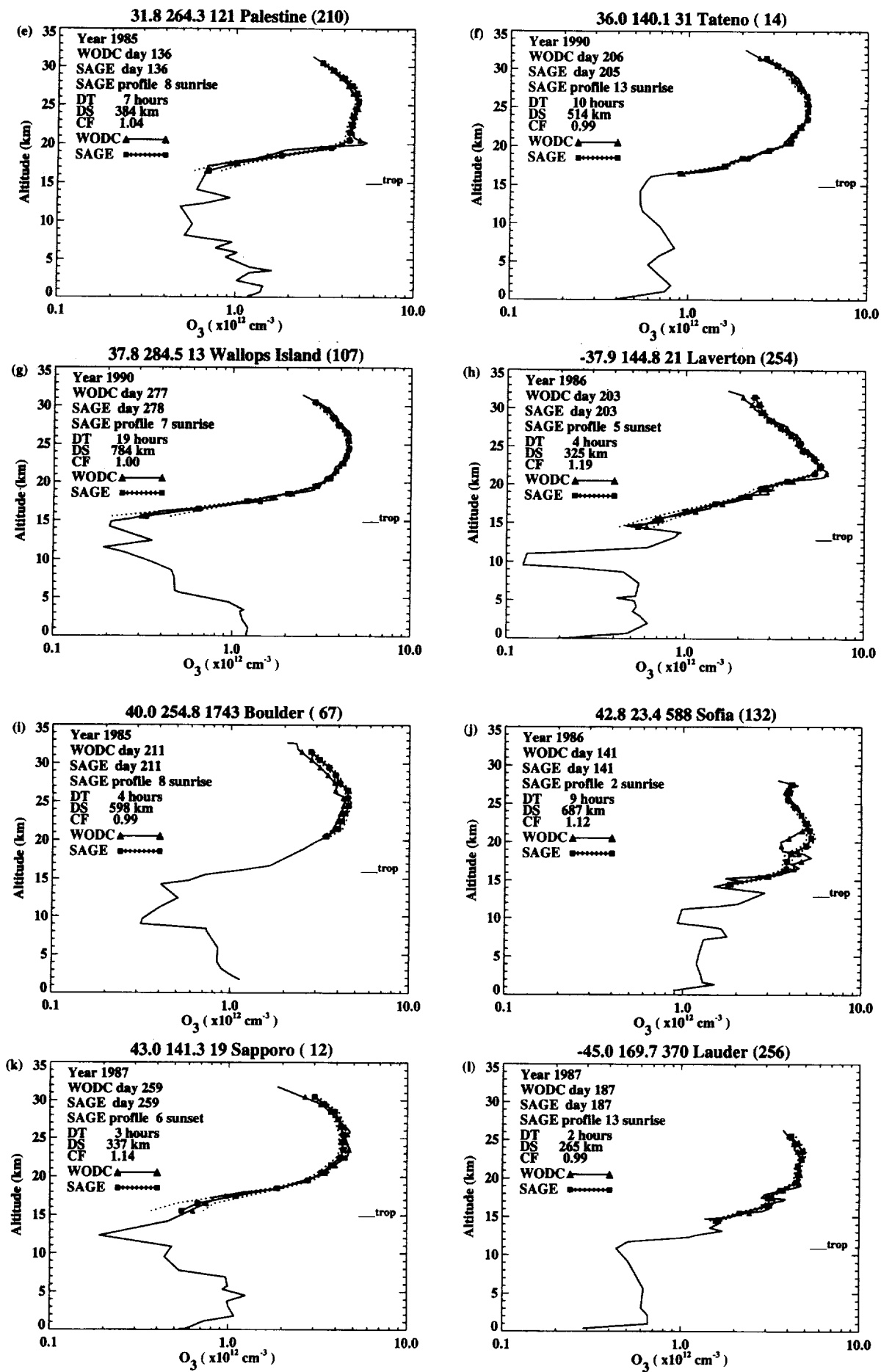


Figure 2. (continued)

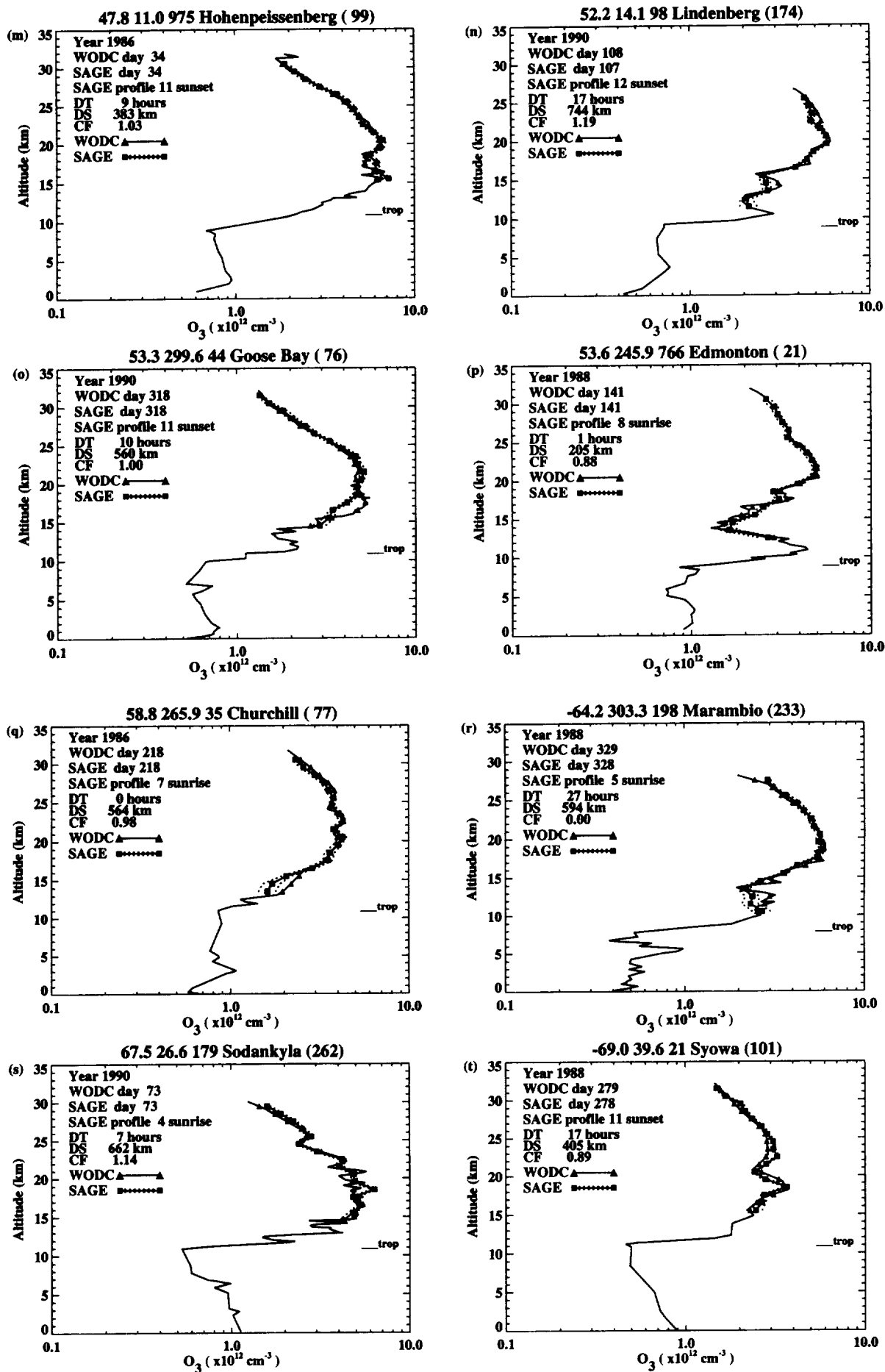


Figure 2. (continued)

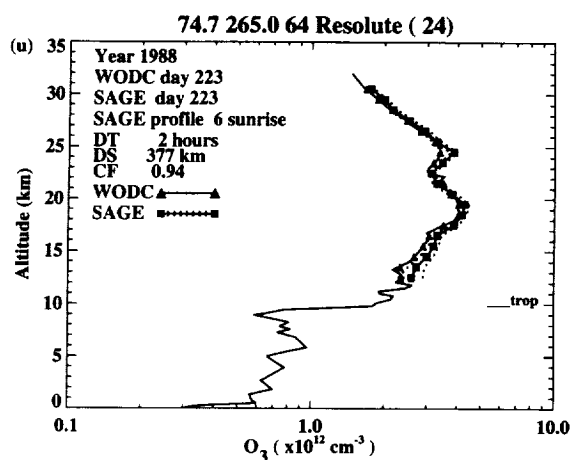


Figure 2. (continued)

Because of the limited data availability, not all years are fully represented, and the reader is referred to Table 1 for the dates. Each panel of difference profiles lists the total number of samples available at each altitude along the right axis. Ninety-five percent confidence intervals are represented by the dotted band. Each profile is shown down to only those altitudes where the length of the 95% confidence interval was less than 20%. Although difference estimates were computed below the lowest altitudes shown in Figures 4 and 5, the combination of small sample sizes along with large variability of the median difference precluded the estimation of the ozonesonde/satellite bias with a high degree of confidence.

For Samoa (Figure 4a), almost all differences are not significant for the altitudes 21.5–31.5 km. The Hilo data (Figure 4b) indicate SAGE II ozone is larger by 8% above 17 km. There is no apparent altitude trend in the difference profile shape, a feature indicative of good altitude registration in the satellite measurement. A characteristic tendency for many comparisons (Figures 4c–4h, 4m, and 4q) is good agreement near the peak of the ozone profile and a subsequent divergence to significant negative differences below the peak. This effect is most pronounced equatorward of 40° and may be related to the steep gradient between the ozone peak and the tropopause at these latitudes. Figure 4e shows the comparison at Palestine which was organized as part of a SAGE II correlative measurement program in 1985. Although the sample size is small, there are no significant differences between 20.5 and 30.5 km. Poleward of 45°, all but one comparison had data extending below 14 km (Figures 4l–4u) which showed no significant differences at the lowest altitudes. The exception is Syowa in Antarctica where the difference is between –10 and –5% below 23 km. This altitude range at Syowa coincides with the ozone depletion region during Antarctic spring when SAGE II samples these polar latitudes densely. Ozone gradients associated with the vortex may have caused the differences in the Syowa comparison. The greatest number of collocations per sampling window size occurred at Hohenpeissenberg (Figure 4m). For this station the difference profile exhibits negative values up to –10% above 32 km and also below the ozone density maximum. The negative differences at the upper altitudes may be due to reduced air pump efficiency of the Brewer–Mast sonde. The largest ozonesonde/satellite

deviations occur in the Lindenberg comparison (Figure 4n) above 25 km where the differences reach –20% at 31.5 km.

An assessment of the relative ozonesonde/SAGE II difference using the difference profiles of Figure 4a–4u was performed by enumerating the differences less than 5% in magnitude at each altitude. These “5%” differences are shown in Figure 4v as the shaded region of a rectangle whose length is the total number of differences for a given altitude. Between 21 and 30 km at least 15 stations had absolute differences less than 5%, with the best count at 24.5 km where all but Hilo agreed to better than 5%. Between 14.5 and 20.5 km and at 31.5 km about half the ozonesondes agreed with SAGE II to within 5%. From the combined stations, differences were estimated at 343 altitudes, and at 240 of those altitudes the median differences were less than 5%.

The comparisons with SAGE I are shown for nine stations in Figures 5a–5i. 95% confidence intervals of length 20% were not available below 15 km. Except for the northernmost station the profiles show increasingly negative values as the altitude decreases below the ozone maximum, culminating in differences between –20 and –10% near 15.5 km. Except for Payerne (Figure 5c), which shows an overall difference of –10%, all the stations agree well near the maximum of the ozone density. At all but one station the differences at the upper altitudes show increasingly negative values with increasing altitude, the extreme case being Resolute (Figure 5i) with –16% at 31.5 km but with few coincident comparisons.

The combined differences for SAGE I are shown in Figure 5j, and are consistent with the SAGE II tabulated differences (Figure 4v) in the altitude range near the ozone maximum. However, below 20 km less than half the stations showed agreement within 5% with SAGE I. No confidence intervals of 20% in length were available below 15 km. From the combined stations, differences were estimated at 138 altitudes, and at 71 of those altitudes the median differences were less than 5%.

The tendency for some of the difference profiles (Figures 4b, 4c, 4d, 4f, 4g, 4h, 4k, 4m, 4p, 4q and Figures 5a–5h) to exhibit trends toward negative values as the altitude decreases below the ozone maximum may, in part, be due to the ozonesonde measurement. In the region of rapid ozone increases above the tropopause, the measured ozonesonde profile is the convolution of the true ozone profile with the sonde instrument temporal response function. *De Muer et al.* [1990] reported better agreement between 24 colocated ozonesonde and SAGE II profiles at Uccle when the instrument response function was deconvolved from the measured sonde profile. Comparisons of the measured ozonesonde profiles at Uccle with their corresponding deconvolved profiles indicate a mean difference (measured–deconvolved) of $-3 \pm 1\%$ at 15 km, whereas at 30 km the mean difference is $6 \pm 1\%$ (D. De Muer, personal communication, 1990). This positive difference at 30 km contrasts with the ozonesonde/SAGE II difference profiles shown in Figure 4 where negative differences appear at 30 km, and may be indicative that declining pump efficiency has a stronger effect than sonde response on the ozone measurement. Additional evidence supporting the sonde temporal response’s effect on the measured profile is found in the BOIC study where differences of approximately 10% between UV photometers and ECCs were recorded in the vicinity of 80 hPa with the UV photometers measuring higher ozone than the sondes. These

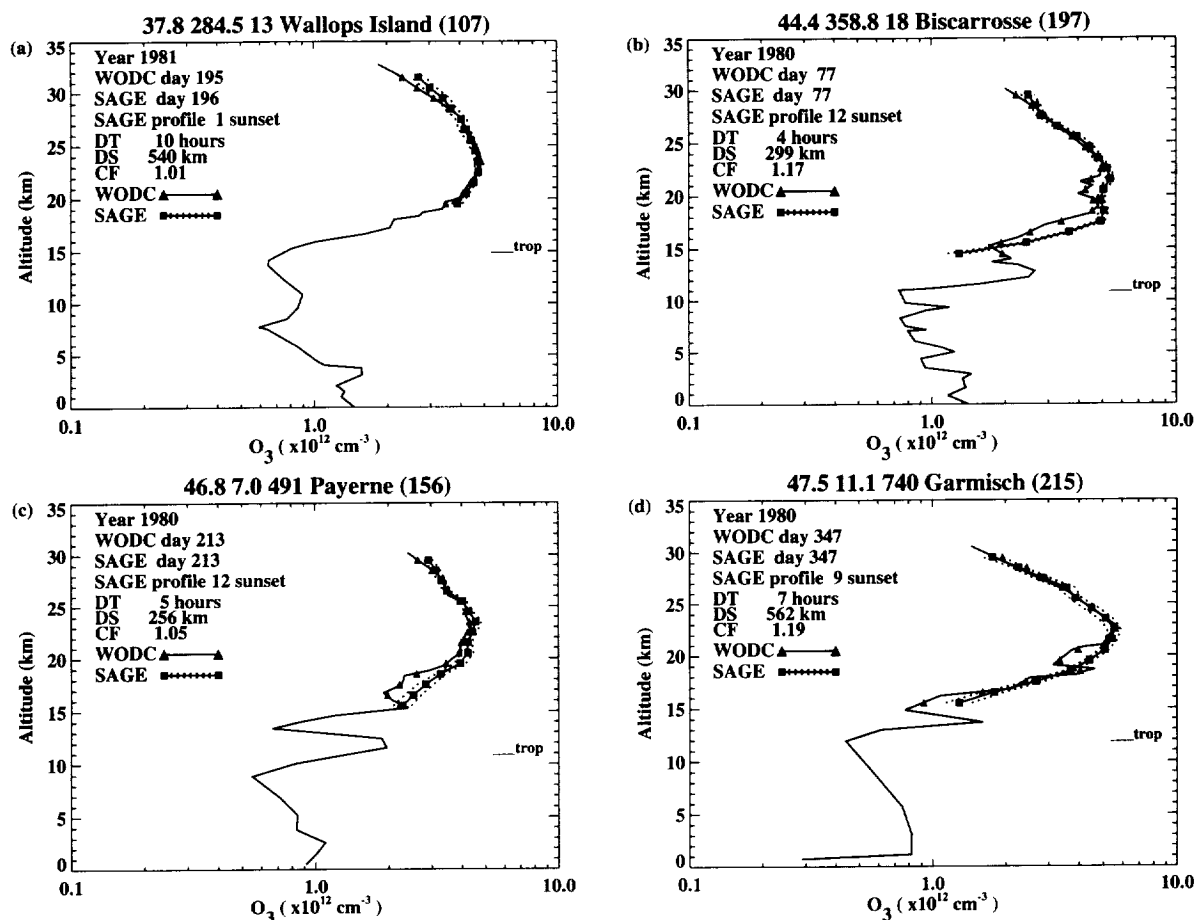


Figure 3. The closest colocated SAGE I and ozonesonde profiles from the ensemble used in calculating median difference profiles. In the legend at the upper left, DT is the time separation rounded to the nearest hour, DS is the spatial separation, and CF is the correction factor. If CF is 0.0, then no correction factor was available for the WODC profile. The approximate height of the tropopause is marked along the right axis. SAGE I data are shown down to the highest detectable cloud. The ozonesonde station's latitude, longitude, altitude (m), name, and number are written along the top of each plot.

differences were attributed to the ECCs lagging the photometers in the altitude region of a high ozone gradient [Hilsenrath *et al.*, 1986]. The difference profiles in Figures 4 and 5 are broadly consistent with those observed in BOIC.

Implications on the SAGE II/SAGE I Difference

The satellite comparisons with the ozonesondes at Wallops Island (Figures 4g and 5a), Hohenpeissenberg (Figures 4m and 5e), Goose Bay (Figures 4o and 5f), Edmonton (Figures 4p and 5g), and Churchill (Figures 4q and 5h) provide an opportunity to address the validity of the lower stratospheric trends computed using the SAGE I and SAGE II data over the period of 1979 through 1991 where trends were computed down to 17.5 km [McCormick *et al.*, 1992]. Implicit here is the assumption that the ozonesonde instrument quality, calibration, and analysis did not change throughout the time period. Comparing the difference profiles at 17.5 km for each of the above stations between the SAGE I and SAGE II time periods reveals that the 95% confidence intervals overlap, and thus it cannot be inferred that the difference between SAGE I and SAGE II ozone at this altitude was nonzero. However, sampling the Hohenpeissenberg data using a larger sampling window reduces the

size of the ozonesonde/SAGE I and II difference profile confidence intervals, and yet the shape and location of the difference profiles are essentially the same as in Figures 4m and 5e. At 17.5 km the ozonesonde/SAGE I difference is -15% while the ozonesonde/SAGE II difference is -9% . This yields a SAGE I/II difference of 6%, and thus within the estimated SAGE I/II uncertainty reported by Watson *et al.* [1988] for the 20 km altitude. Thus we cannot conclude, based on the Hohenpeissenberg data alone, that the SAGE I/II difference at 17.5 km is statistically significant.

Aerosol Correlation and Temporal Stability

The relatively large paired data sample (1 day and 1000 km) available at Hohenpeissenberg was used to assess the potential influence of a wide dynamic range in aerosol extinction on the ozonesonde/satellite difference. Figure 6 shows the 1020 nm SAGE II aerosol extinction coefficient at 18.5 km in a 10° latitude band centered over 48°N , the latitude of Hohenpeissenberg. Near 18.5 km the extinction profile takes on its stratospheric maximum at these latitudes, and thus the time series in Figure 6 approximates, up to a scaling constant, the time history of stratospheric optical depth for this latitude band. It can be seen that the extinction

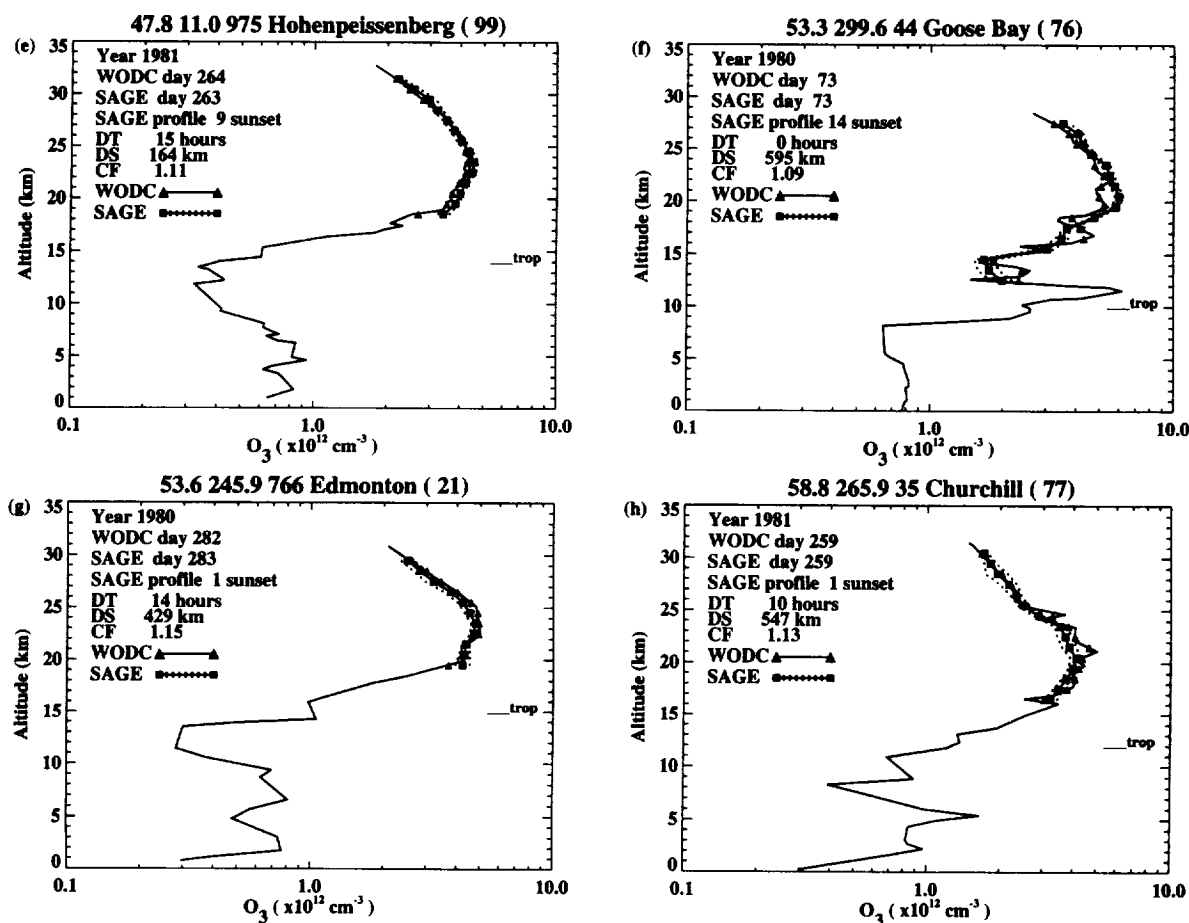


Figure 3. (continued)

time history began a decline from the large values in 1984–1985, which were predominantly the volcanic aerosol remnants of the 1982 eruption of El Chichón (18°N), to highly variable values in early 1986 driven by the Nevado Del Ruiz (5°N) eruption in late 1985, and subsequently to the low values in early 1991. Each year was punctuated by large winter variances induced by the intrusion of polar air masses and small summer variances. Significant stepwise decreases in the mean aerosol amount occurred during the springs of 1985, 1988, and 1991 and may be related to QBO modulated advection to the high latitudes. After mid-1991, the Mount Pinatubo (15°N) eruption caused large increases in extinction [McCormick and Veiga, 1992].

To assess the potential impact of less extreme aerosol loading than that produced by Mount Pinatubo, the ozone-sonde/SAGE II differences at Hohenpeissenberg were analyzed in order to determine whether a time dependent correlation existed between the ozone differences and aerosol extinction. The presence of larger correlations during periods of time when the aerosol extinction was higher than during periods when the extinction was lower would be indicative that the SAGE II ozone retrieval contained an aerosol residual. Several time periods of varying length were chosen so that each period could be clearly classified as having high, medium, or low aerosol amount (Figure 6: 1984–1985, 1986–1987, and 1989–1990, respectively). Correlation coefficients of the ozonesonde/SAGE II difference versus the SAGE II 1020 nm extinction were computed over

the altitude range from 10.5 to 32.5 km, and the resulting set of three correlation profiles possessed a high degree of similarity irrespective of the period each represented. The temporal constancy of the correlation profile indicates that for the aerosol levels encountered between late 1984 and mid-1991, the SAGE II ozone retrieval algorithm effectively accounted for aerosol extinction.

The solid curve in Figure 7 shows the mean of an ensemble

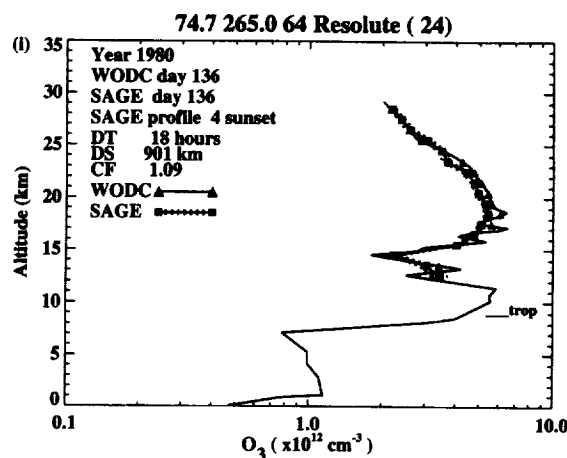


Figure 3. (continued)

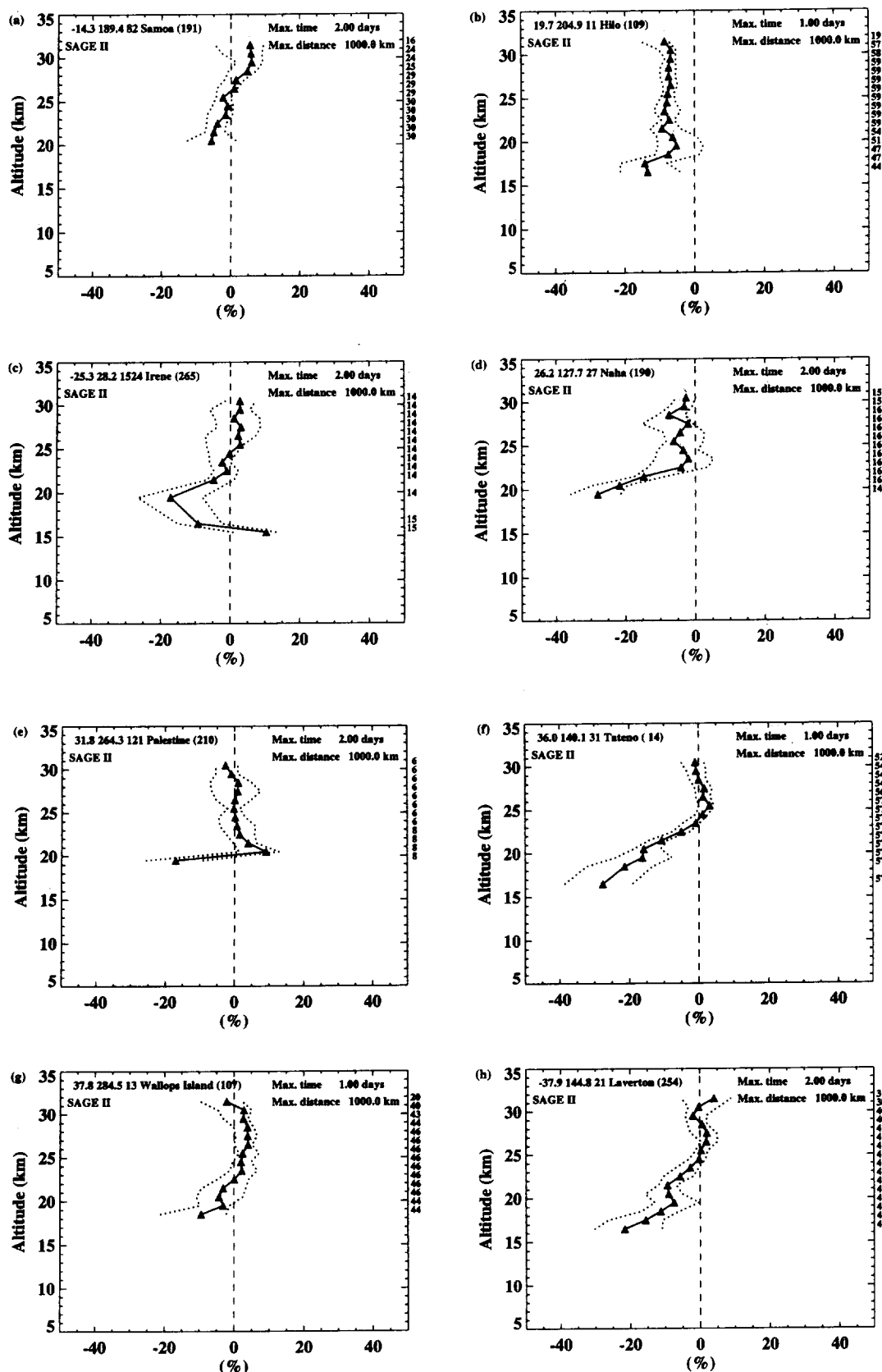


Figure 4. Median difference profiles for the ensemble of ozonesonde/SAGE II paired data. See Table 1 for the applicable dates. The units are in percentage relative to SAGE II. The dotted band represents the 95% confidence interval of the median difference. Only confidence intervals whose length is less than 20% are shown. Samples sizes at each altitude are marked along the right axis. Figure 4v is a compilation of the frequency with which the combined ozonesonde/satellite differences were less than 5%. Each open bar represents the total number of sample differences available for a given altitude, and the shaded bar is the number of sample differences less than 5%.

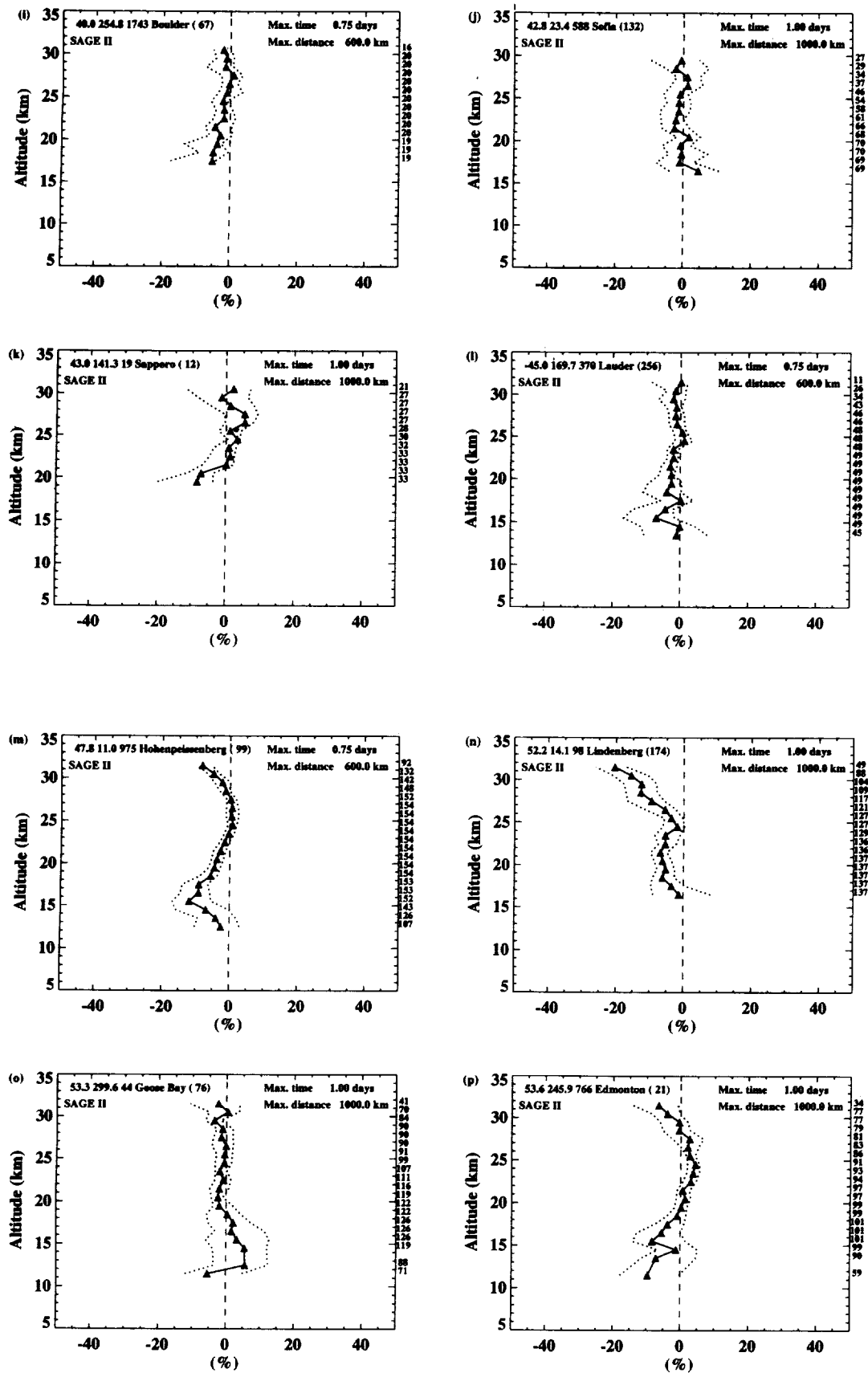


Figure 4. (continued)

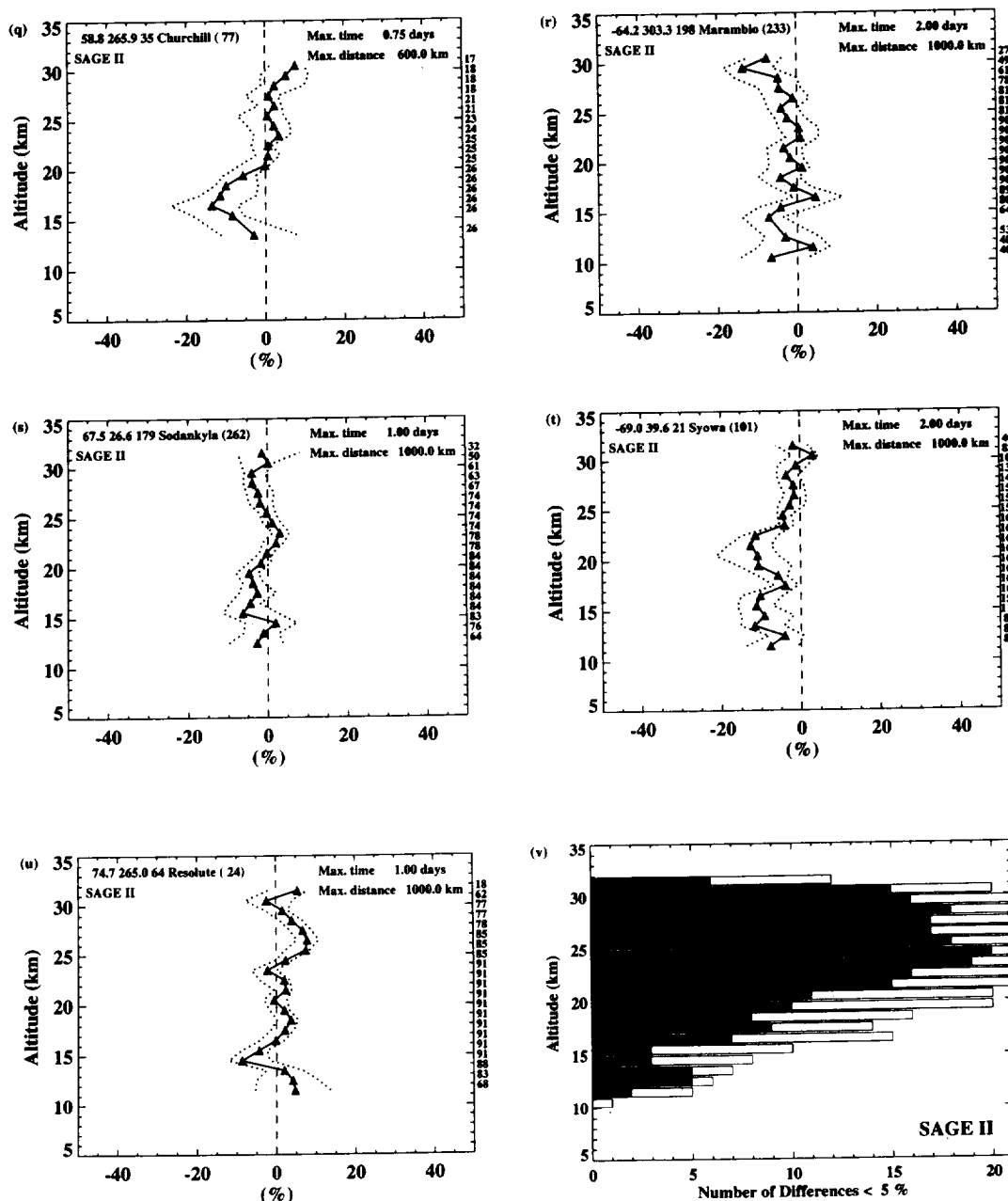


Figure 4. (continued)

of correlation profiles of SAGE II/ozonesonde ozone difference versus extinction (note this is the negative of the correlation profile discussed above). It would be expected that if the satellite and ozonesonde agreed exactly, or if their difference were random, the correlation profile would be zero. The vertical structure in the SAGE II/ozonesonde difference versus extinction correlation indicates the existence of a residual bias between the two ozone measurement systems, or an ozone retrieval effect, or an intrinsic property of the vertical structure of the stratosphere. To show evidence for the latter, the correlation between the SAGE II ozone and SAGE II extinction for the paired data sampling over Hohenpeissenberg is shown in Figure 7 as the dotted curve, and similarly the dashed curve is the correlation between ozonesonde ozone and SAGE II extinction. Clearly, both these correlation profiles have an almost

identical vertical structure although the magnitudes differ. Since the sonde ozone is a measurement independent from the SAGE II extinction, the vertical structure of the correlation of SAGE II ozone and SAGE II extinction cannot be due solely to satellite ozone retrieval aerosol effects. The differences in magnitudes between the dashed and dotted curves can be explained by the fact that the ozonesonde measurements are not exactly colocated in time and space with the satellite extinction measurements, and hence the ozonesonde versus extinction correlation is always less in magnitude than the satellite ozone versus satellite extinction correlation. *Cunnold and Veiga [1991]* proposed that the vertical structure of the correlation between ozone and extinction is produced by horizontal and vertical advection of the constituents.

The ozonesonde/SAGE II difference profiles computed

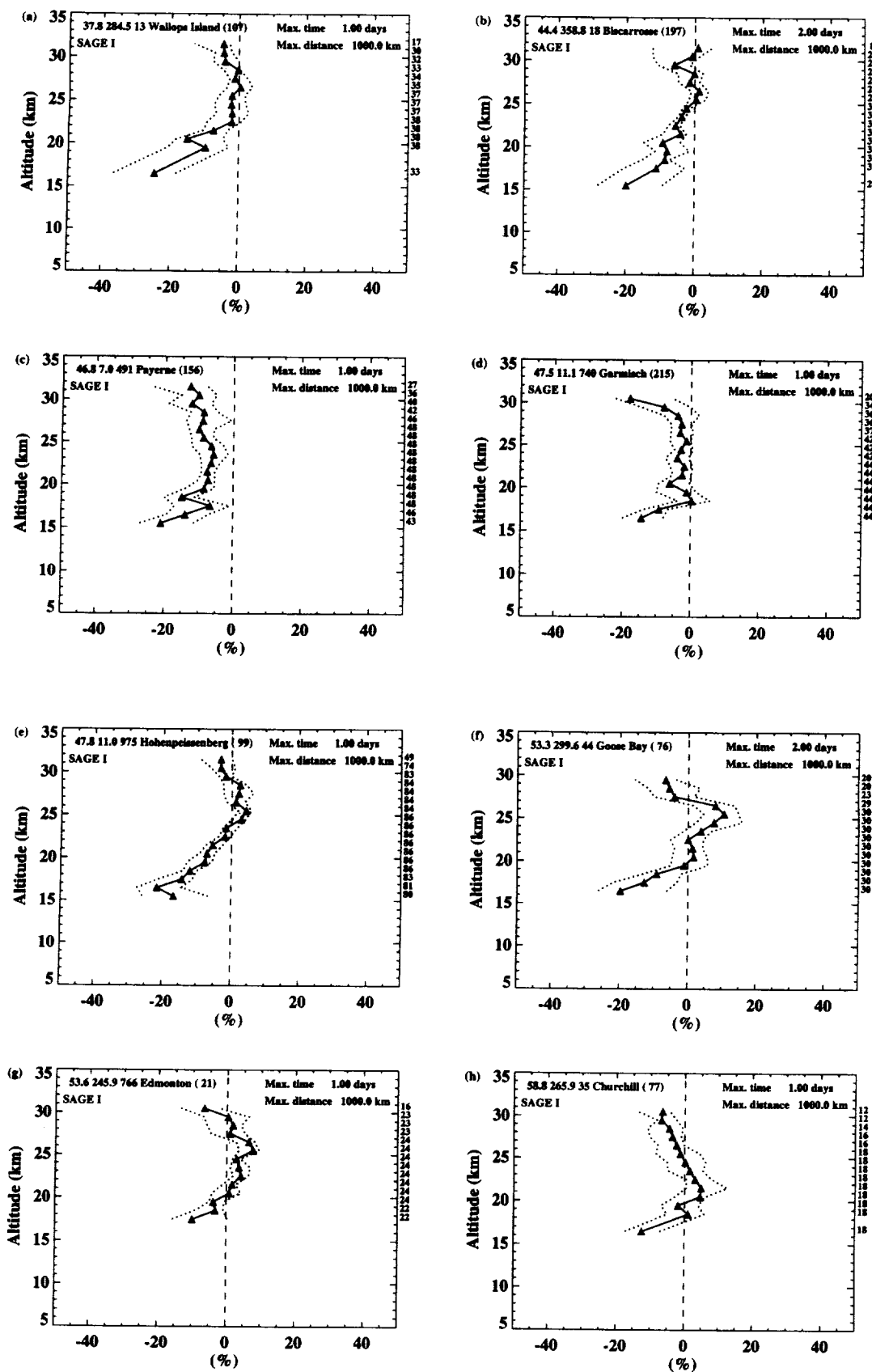


Figure 5. Median difference profiles for the ensemble of ozonesonde/SAGE I paired data. See Table 1 for the applicable dates. The units are in percentage relative to SAGE I. The dotted band represents the 95% confidence interval of the median difference. Only confidence intervals whose length is less than 20% are shown. Sample sizes at each altitude are marked along the right axis. Figure 5j is the same as in Figure 4v.

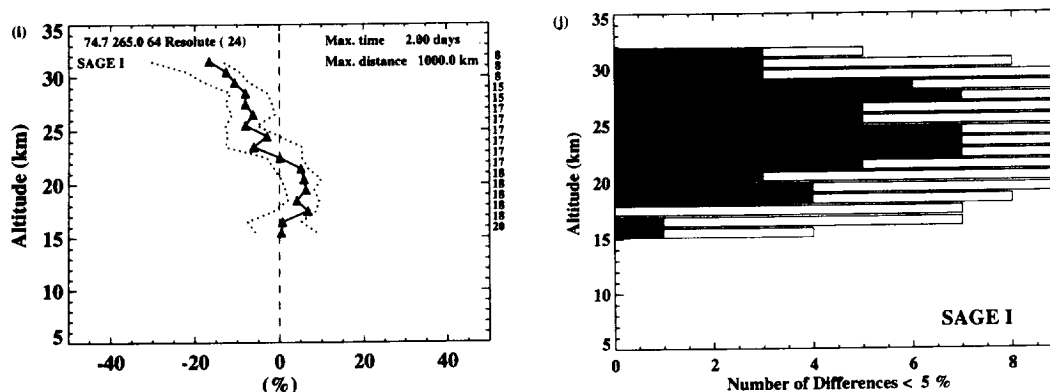


Figure 5. (continued)

during varying aerosol conditions and seasons are shown in Figure 8. Figure 8a shows the difference profiles computed for three periods ranging from high to low aerosol extinction levels. The shaded band is the envelope of the 95% confidence interval at each altitude. The differences between any pair of the three profiles shown were not significant at any altitude, and hence these results indicate that the relative difference between the SAGE II ozone measurements and the ozonesondes over Hohenpeissenberg were temporally constant. Figure 8b shows the difference profiles from seasonal sampling of the period from late 1984 through mid-1991. Occultation sampling allowed the most overpasses during the fall and winter, while the summer months were sampled less frequently, and consequently little data were available below 15 km during the June through August time

period. The seasonal variation of the mean tropopause is shown by the tropopause altitudes during winter and summer at this location. Since the 95% confidence intervals for any given pair of difference profiles overlapped, these data indicate that there were no significant seasonal biases in the ozonesonde/SAGE II difference.

It must be emphasized that the results above are derived from analyzing the data over the midlatitudes between 1984 and mid-1991, and that possible aerosol/ozone correlations in the SAGE II data may exist at other latitudes. Analysis of the SAGE II data after the eruption of Mount Pinatubo indicates that the ozone is not correlated with aerosol extinction whenever the $1 \mu\text{m}$ extinction is less than 0.001 km^{-1} . While the midlatitudes never attained extinction values larger than this prior to the Mount Pinatubo eruption,

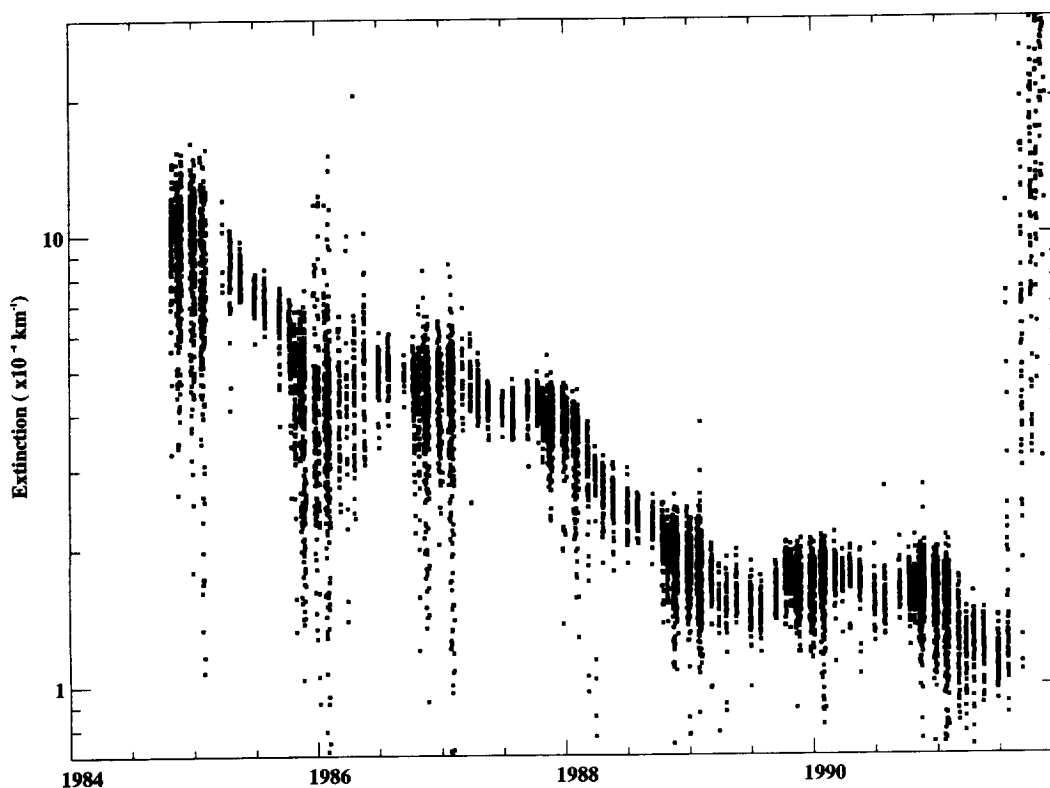


Figure 6. SAGE II 1020 nm extinction at 18.5 km over the latitude band extending from 43°N to 53°N.

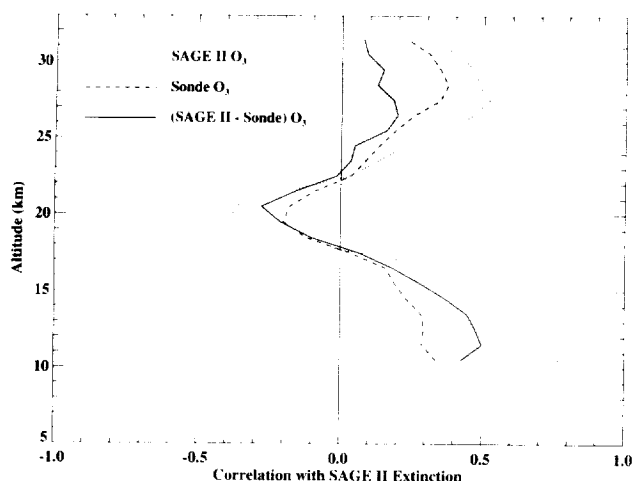


Figure 7. Mean correlation between SAGE II ozone versus SAGE II extinction (dots), ozonesonde ozone versus SAGE II extinction (dashes), and (SAGE II/ozonesonde) ozone difference versus SAGE II extinction (solid). Each profile was computed by averaging an ensemble of correlation profiles where each correlation profile in the ensemble represented a 1-year data sample. The 1-year sampling window was shifted in 45 day increments from late 1984 through mid-1991 in generating each correlation profile of the ensemble. The SAGE II and ozonesonde paired data profiles within each sampling window were colocated to within 1 day and 1000 km over Hohenpeissenberg.

there were larger values in the tropics following the eruption of Nevado del Ruiz.

Conclusions

We have sampled the ozonesonde in situ profile and SAGE I/II satellite profile databases within a temporal/spatial coincidence window, whose nominal size is 1 day and 1000 km, in order to isolate colocated profile pairs from which to estimate any possible relative differences between the two ozone measurement systems. We have also assumed that an acceptable estimator of the relative difference is the sample median whose 95% confidence interval has a length less than 20% and used this criterion to select the size of the temporal/spatial sampling window. Median differences not satisfying these criteria were not considered in the study.

Profile pairs were colocated at 21 ozonesonde stations with SAGE II overpasses and at nine stations with SAGE I overpasses. The magnitude of the median difference averaged over all altitudes was $6 \pm 2\%$, for the 21 closest possible coincides with SAGE II, and $8 \pm 3\%$ for the nine closest coincidences with SAGE I. Using the statistical sampling criterion above, the lowest altitudes at which comparisons were possible with SAGE II were between 15.5–20.5 km equatorward of 45° and 11.5–13.5 km poleward of 45° . For nine stations with SAGE I overpasses (38°N – 75°N) the lowest altitude at which comparisons were possible was 15.5 km.

On the whole, the comparisons between ozonesondes and SAGE I and II ozone measurements indicated agreement well within the errors attributable to either system. Individual profile pairs showed that fine-scale ozone variations were well resolved by SAGE when both systems sampled the

same air mass. Using the statistical sampling criterion, the ensemble of ozonesonde/SAGE II differences, taken over all altitudes, agree within 5% for 70% of all the possible comparisons, while for SAGE I 50% agreed to within 5%.

The largest differences ranged between -5 and -30% and were found in the lower stratosphere in the region of maximum ozone gradient between the altitudes from 15 to 20 km. Most of the comparisons with SAGE I showed statistically significant differences at the lowest altitudes, whereas SAGE II showed better agreement at these altitudes. At several stations, differences were large and negative above the tropopause and decreased in magnitude toward zero at the ozone maximum, a feature partly ascribable to hysteresis in the ozonesonde measurement. The best ozonesonde/satellite comparisons were found in the altitude range near

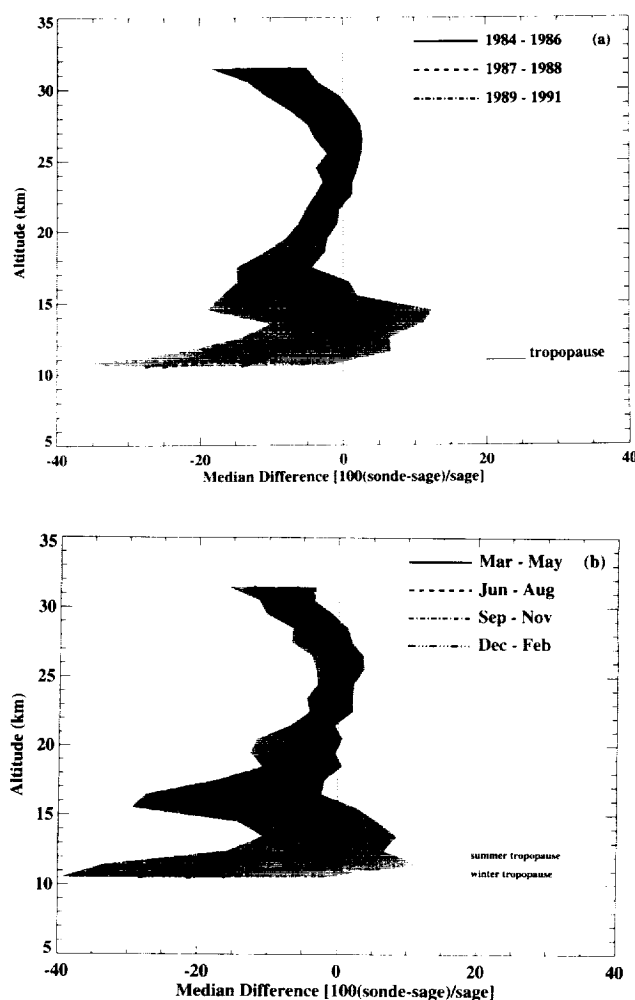


Figure 8. Ozonesonde/SAGE II difference profiles computed from paired profiles colocated to within 1 day and 1000 km over Hohenpeissenberg. (a) Difference profiles representing the periods of late 1984 through 1986 (170 profile pairs), 1987 through 1988 (192 profile pairs), and 1989 through mid-1991 (175 profile pairs). (b) Seasonal difference profiles representing spring (83 pairs), summer (29 pairs), autumn (183 pairs), and winter (179 pairs). The shaded band represents at each altitude the envelope of the 95% confidence interval taken from the enclosed profiles. Too few data were available below 15 km in during the summer season.

the ozone maximum (21–26 km), where essentially all comparisons showed differences less than 5%.

The selection of the ozone profile pairs based solely on a specific temporal/spatial sampling window (up to 2 days and 1000 km) inevitably includes a relatively large number of cases where the paired profiles represented different synoptic conditions. As a consequence the large sizes of the 95% confidence intervals at lower stratospheric levels shown in Figures 4, 5, and 8 contain a geophysical component. One method of accounting for the synoptic component is to use a back-trajectory analysis to properly compare ozone measurements from similar air masses. This would probably improve the confidence in the lower stratospheric comparisons.

Analysis of the correlation between aerosol extinction and ozonesonde/SAGE II differences at one northern midlatitude station revealed that the SAGE II ozone retrieval was not affected by the levels of aerosol encountered in the lower stratosphere in the time period between late 1984 and mid-1991. A temporally invariant vertical structure in the correlation profile between ozone and extinction appears in both the SAGE II ozone data and in the ozonesonde data and is possibly indicative of transport processes in the stratosphere. During the time period from late 1984 through mid-1991 the ozonesonde/SAGE II difference profile showed insignificant changes in the lower stratosphere (below 20 km) as the extinction varied by an order of magnitude throughout the period. No significant seasonal biases in the difference profiles were detected.

Acknowledgments. We thank S. J. Oltmans for providing the Hilo, Samoa, and Boulder ozonesonde data; W. A. Matthews for providing the Lauder ozonesonde data; D. De Muer for providing the SAGE II and Uccle comparison profiles; C. Trepte, and J. Zawodny for valuable discussions. R. Veiga was supported by NASA contract (NAS1-19570). D. M. Cunnold was supported by NASA contract (NAS1-19954).

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(Received June 28, 1994; revised December 1, 1994;
accepted December 3, 1994.)